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Title: High-Resolution 3D Acoustic Borehole Integrity Monitoring System

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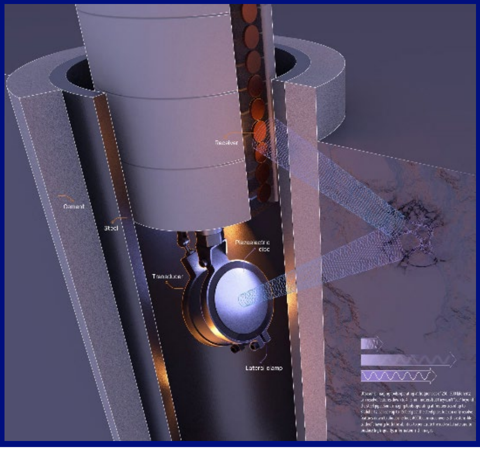
Los Alamos
NATIONAL LABORATORY

High-Resolution 3D Acoustic Borehole Integrity Monitoring System

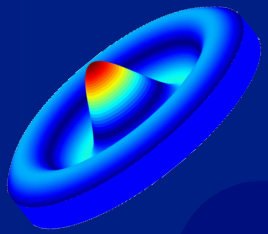


Project Number: FWP-FE-855-17-FY17

Cristian Pantea

Applied Acoustics Lab

Los Alamos National Laboratory



LA-UR-21-XXXXX

U.S. Department of Energy

National Energy Technology Laboratory

Final Project Presentation with Los Alamos National Laboratory - FWP-FE-855-17-FY17

Webex

27 September 2021

Partners/Collaborators

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Presentation Outline

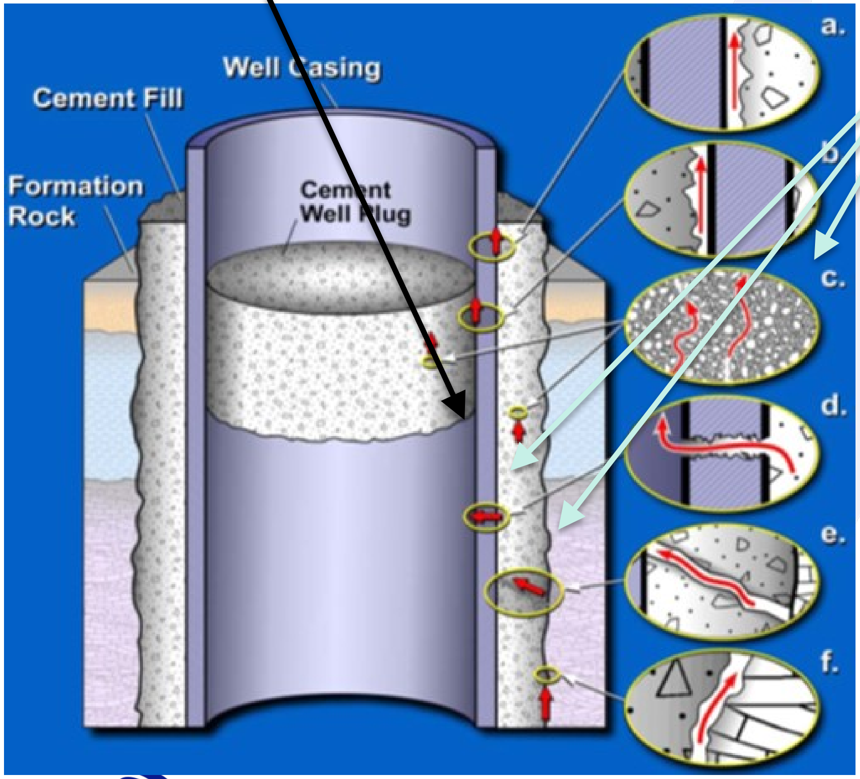
- Technical Status
- Accomplishments
- Project Summary

Technical Status

Develop a high-resolution 3D imaging system for improved wellbore diagnostics and integrity assessment

Existing ultrasonic tools work well for casing inspection

Extend applicability to: (1) casing-cement interface, (2) cement-formation interface, and (3) out in the formation (up to ~ 3 meters).



* Picture adapted from S.E. Gasda, Environ Geol (2004) 46: 707-720

Performed a comprehensive literature/existing technology study for wellbore integrity monitoring tools.

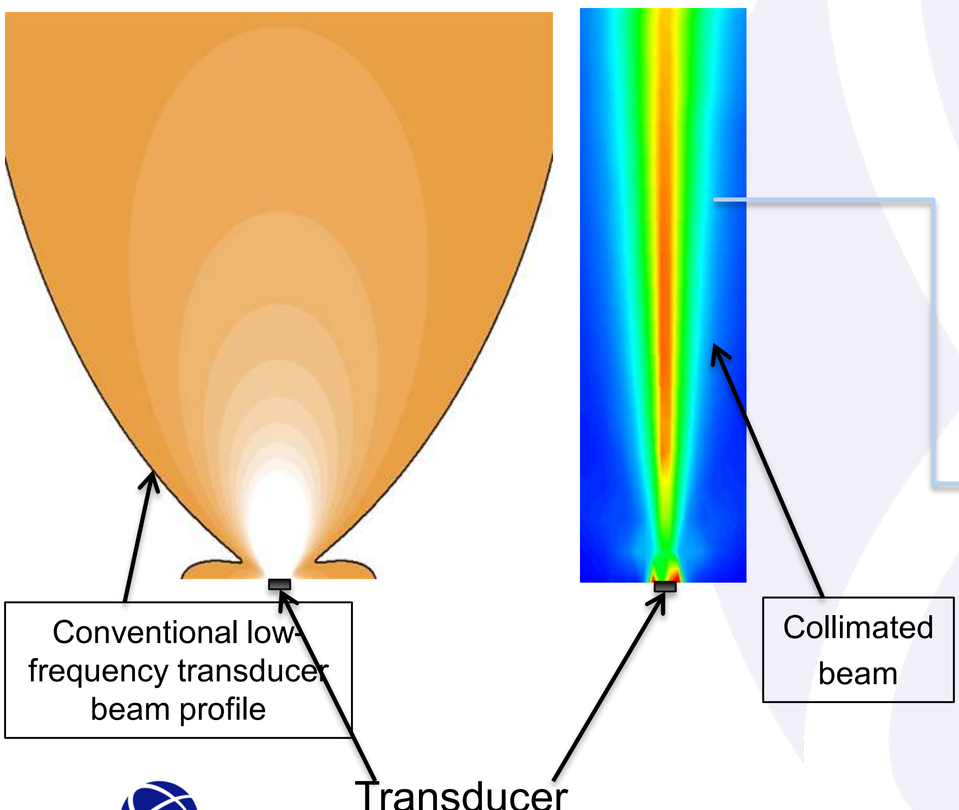
Comparison of existing techniques and the present approach

Method	Frequency (kHz)	Range (m)	Resolution (mm)
Sonic probe	0.3-8	15	~ 300
Present approach	10-150	~ 3	~ 5
Ultrasonic probe	>250	casing	4-5

Technical Status

The Proposed Approach:
Novel technique that fills this technology gap.

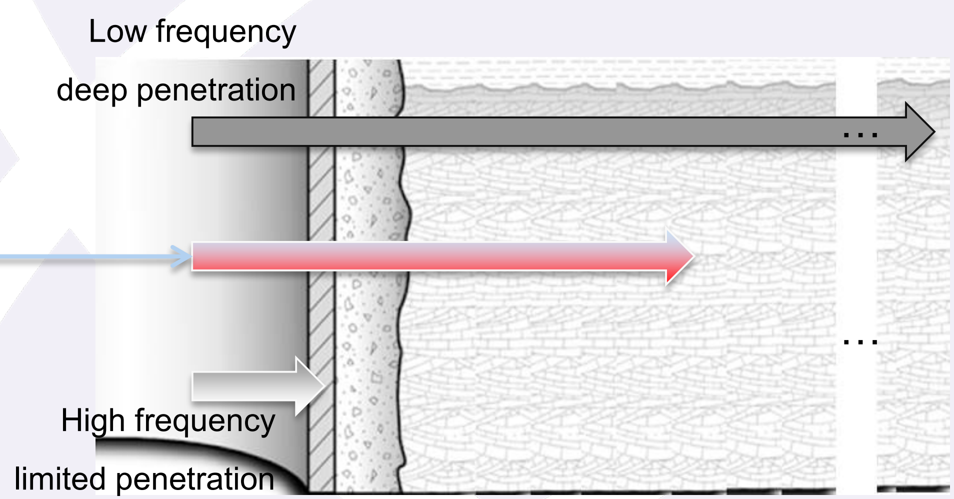
1. Collimated beam for increased resolution



2. Low frequency for deeper penetration

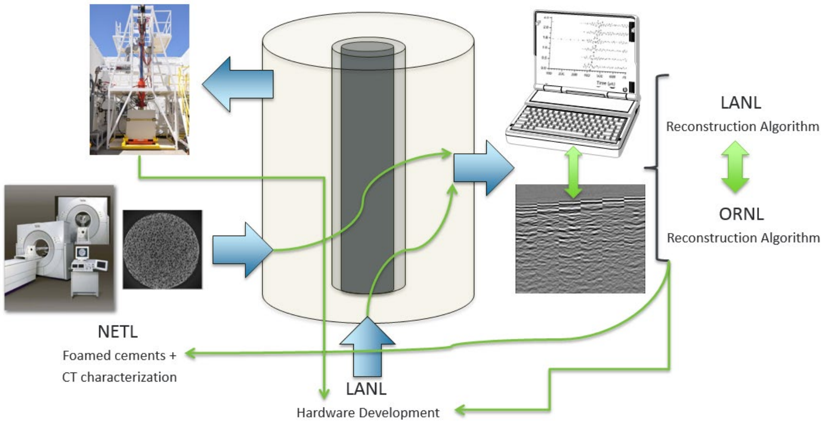
$$Attenuation \sim f^{n}$$

f = frequency, n = 1-2



Technical Status

Multi-lab project



Inter-lab collaboration and teaming arrangements/partnerships

- Develop acoustic source, imaging system, and image processing.
- Investigate acoustic metrics for foamed cements. Incorporate new metrics for wellbores in the field.
- Explore different image processing approaches.
- Perform experiments in more realistic boreholes. Incorporate data from realistic borehole and compare resolution with lab experiments.

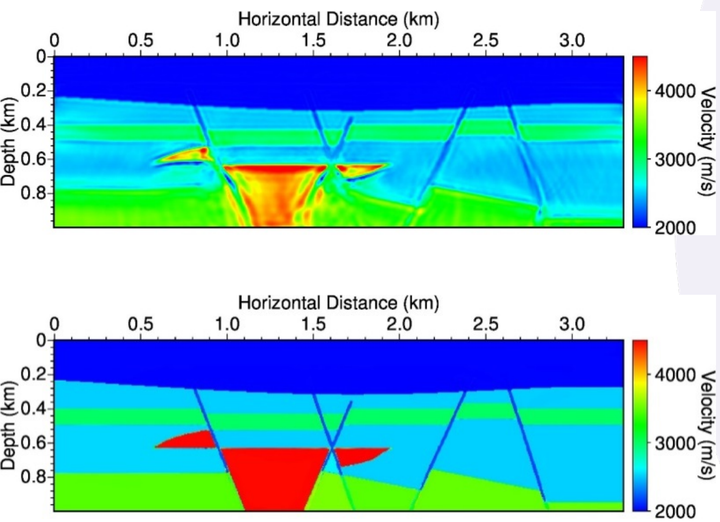
Technical Status

Advanced image processing techniques:

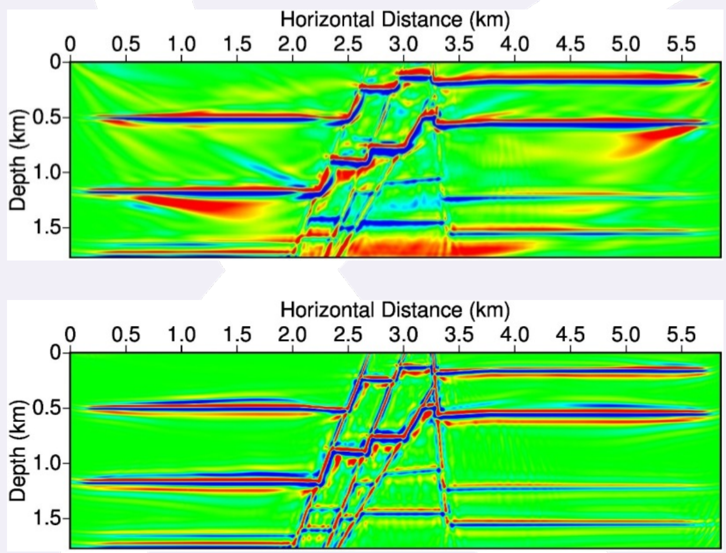
(1) LANL's Elastic-Waveform Inversion,

(2) LANL's Least-Squares Reverse-Time Migration techniques,

(3) ORNL's model-based iterative reconstruction (MBIR).



(1)



(2)

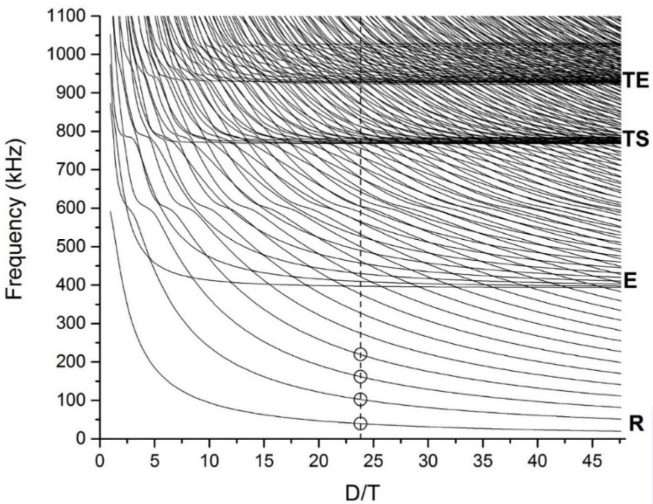
conventional

enhanced

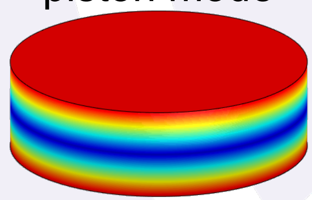
(3)

Accomplishments

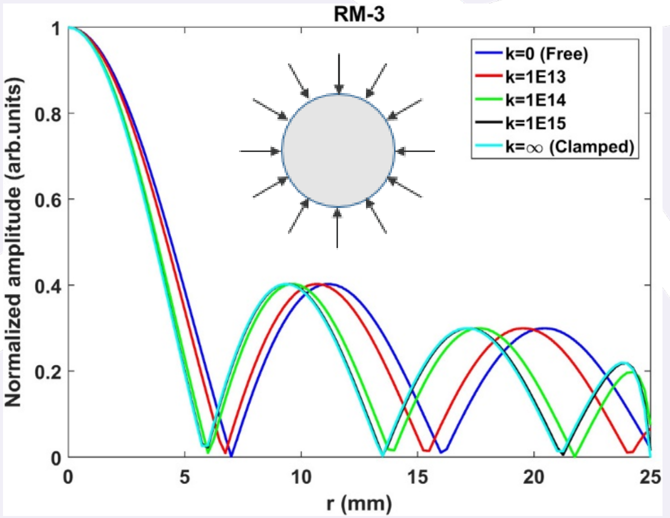
Generate collimated beam by exciting radial modes of piezoelectric disk
Clamp disk edges to focus energy into collimated beam

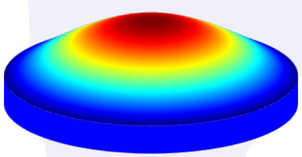


Traditional acoustic source "piston mode"

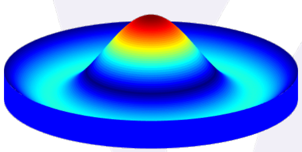


Normalized out-of-plane displacement on the surface of the disc for RM-3 for different lateral stiffness k (N/m3)

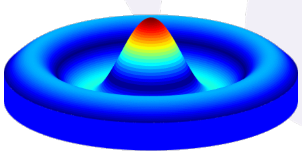




Radial mode 1

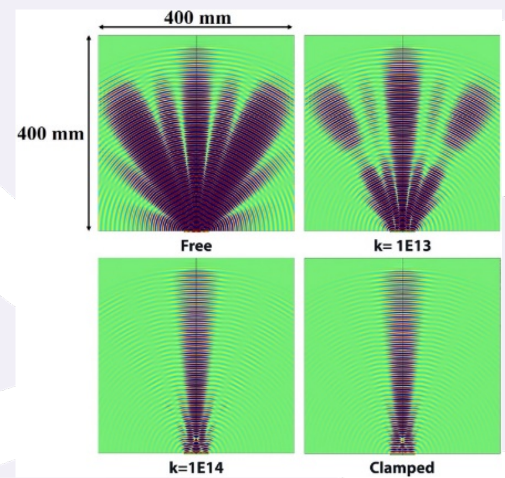


Radial mode 2

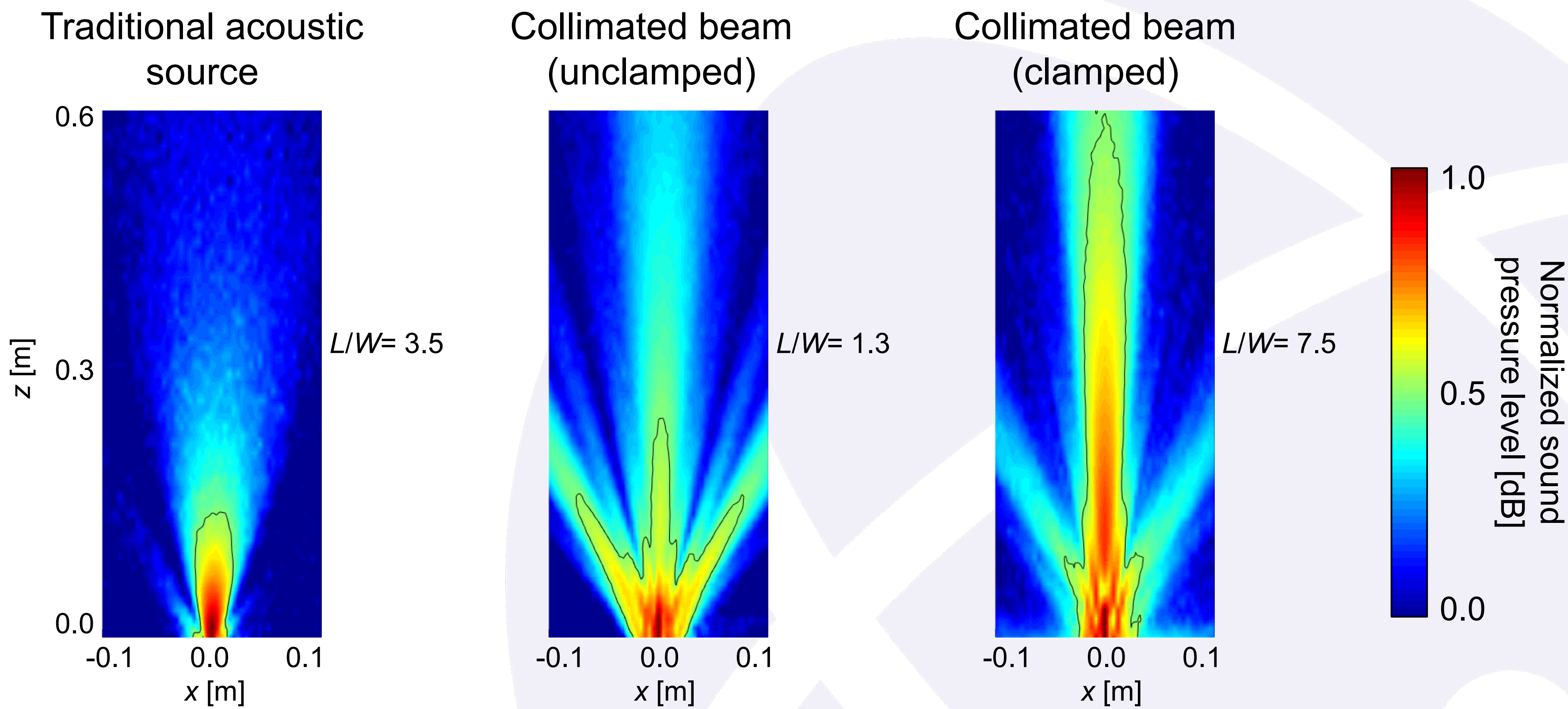


Radial mode 3

Rev. Sci. Instrum., vol. 91, (2020), 075115.
Smart Mater. Struct., 2020, vol. 29, 085002
Ultrasonics, 2019,vol. 96, no. 7, pp. 140-148
AIP Conf. Proc., 2019, vol. 2102, pp. 040013
Appl. Phys. Lett., 2018, v. 113, issue 7, p. 071903
Wave Motion, 2018, vol. 76, p. 19-27
Appl. Phys. Lett., 2017, v. 110, issue 6, p. 064101
Proceedings of SPIE, 2017, v. 10170, p. 1017024
POMA, vol. 32(1), (2017), pp. 045013



Accomplishments



Collimated beam provides:

- Reduction in beam width → higher image resolution, more control over directivity
- Increased beam length → longer detection/communication range

Accomplishments

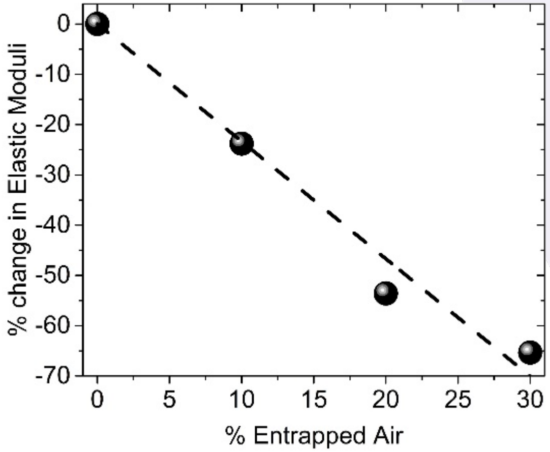
Elastic Properties of Foamed Cement

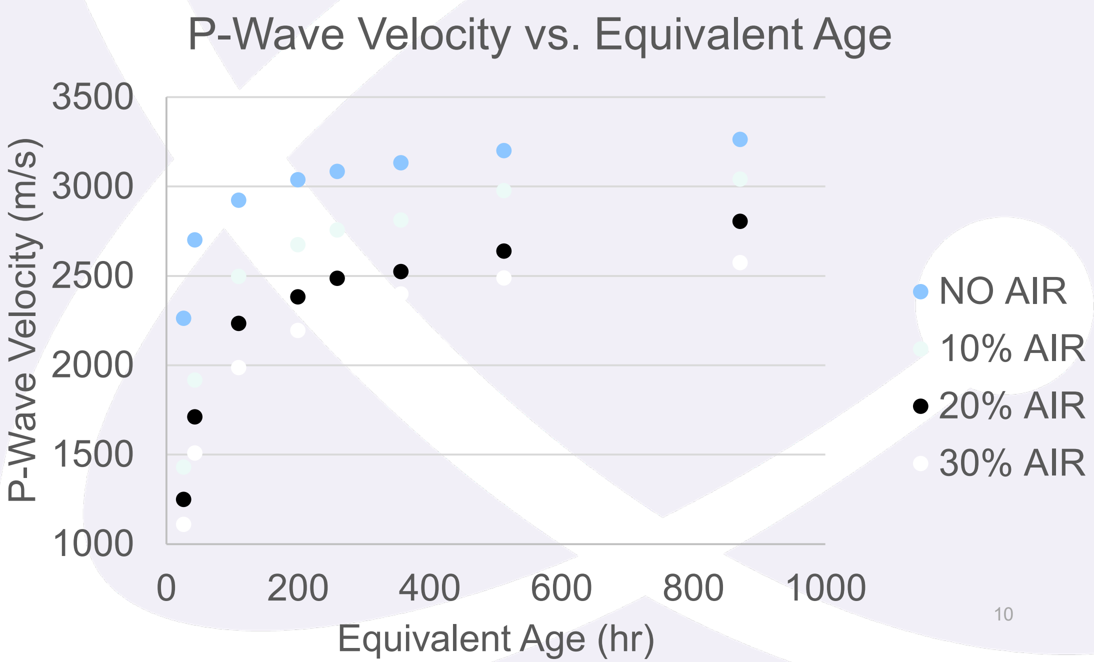
- Ultrasonic testing of Foamed Cement cylinder specimens with size approximately 25 mm (diameter) x 110 mm.
- Equivalent Age was calculated using the Arrhenius equation with an Activation Energy of 35,418 J/mol.

Case (Foam Quality)	0%	10%	20%	30%
P-Wave Velocity+ ($^{m}/_{s}$)	3371.5	3060.4	2877.6	2661.8
Mass Density+ ($^{kg}/_{m3}$)	2120.9	1853.2	1650.3	1468.4
Poisson's Ratio*	0.18	0.18	0.19	0.2
Young's Modulus (GPa)	22.2	15.48	11.9	8.8

+ measured, *assumed

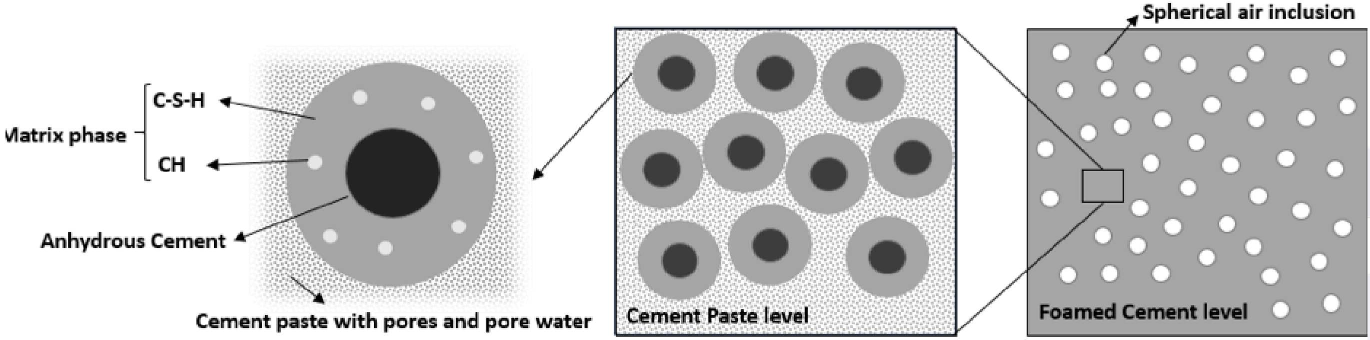
LANL got similar values for v_p. Measured v_s. Poisson ratio was determined to be ~0.25, using measurements of both longitudinal and shear propagation modes.
Large change in elastic moduli with air content → significant softening



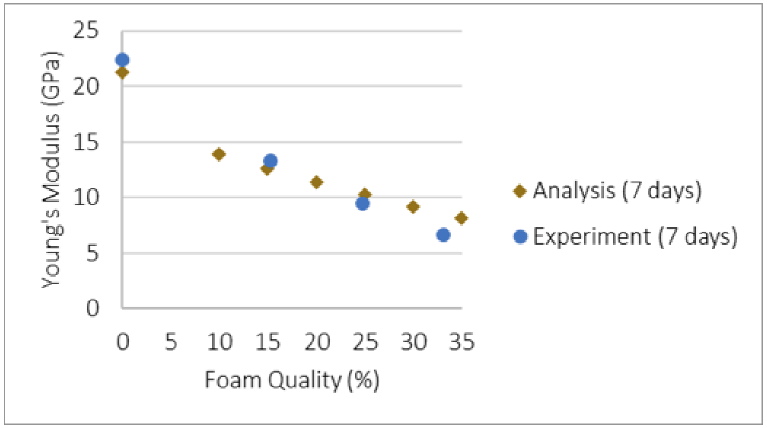


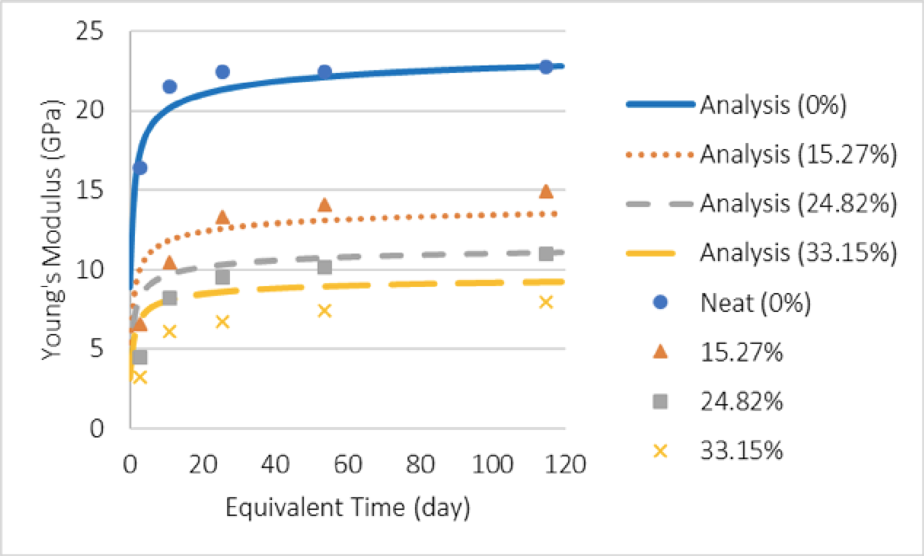
Accomplishments

Modeling of Mechanical Properties



- The effective medium theory was used to calculate Young's modulus of cement paste and foamed cement with different foam qualities.
- Both analytical and experimental results show that the Young's modulus tends to reduce as the foam quality increases.





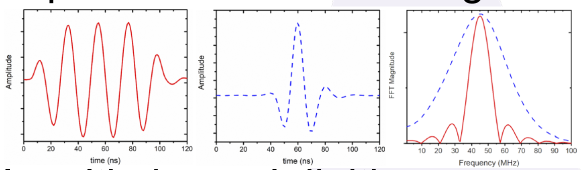
	0%	10%	20%	30%
ρ(g/ml)	2.0631	1.7481	1.5510	1.3791
Air%	-	15.27%	24.82%	33.15%

Accomplishments

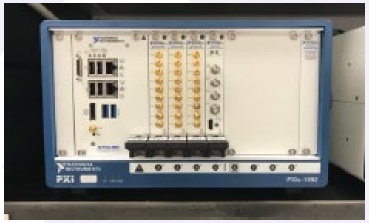
Tool improvement:

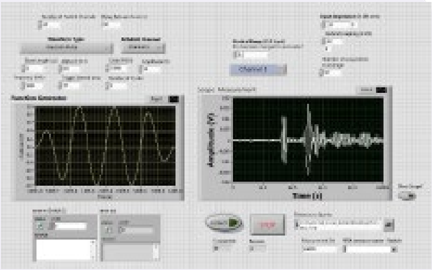
- Increased efficiency by ~2 orders of magnitude
    - Previous source based on nonlinear mixing (~0.1% efficiency)
    - New source based on clamped radial modes

- Increased data collection speed by ~2 orders of magnitude
    - Shaped waveform with large bandwidth



    - NI multi-channel digitizer
      (leveraging on a high-explosive project)

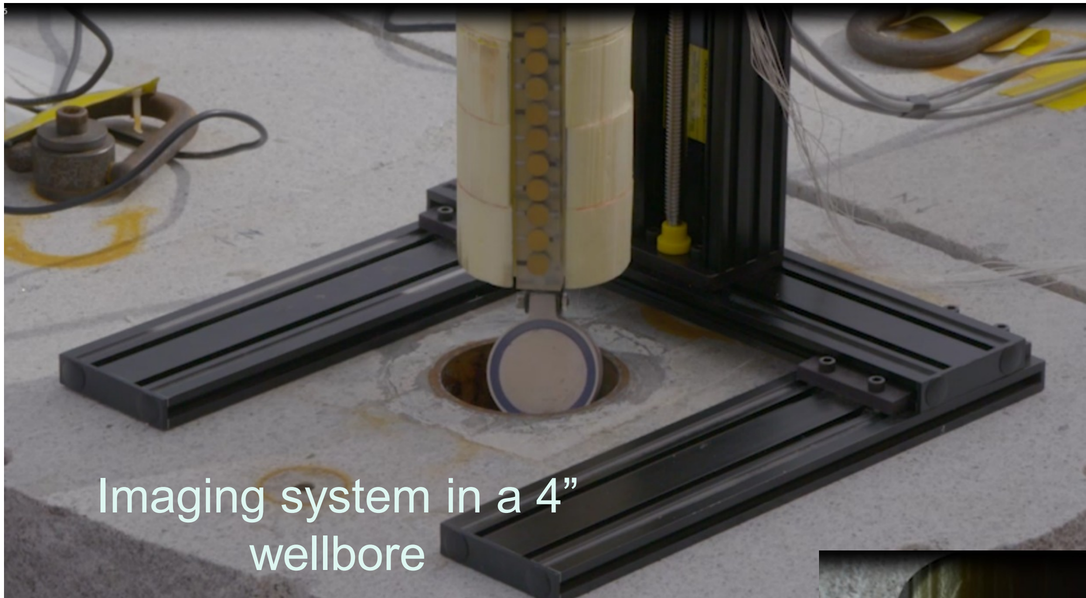


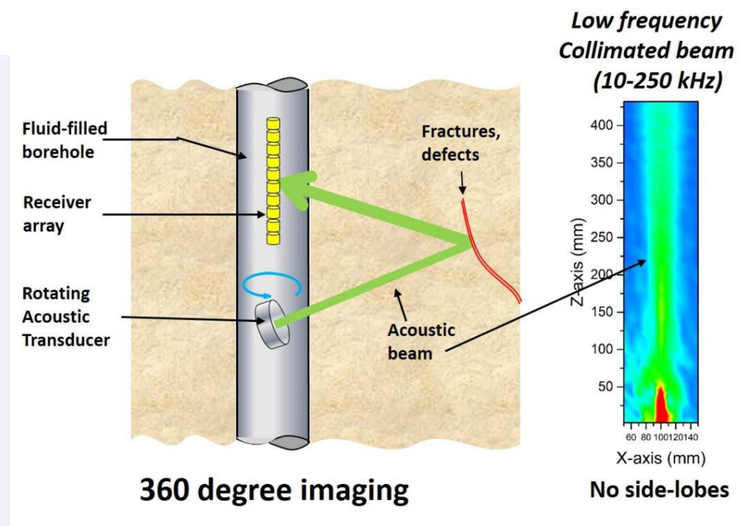


- Ruggedized tool
    - Stainless steel and ceramic parts for sensor packaging and cables

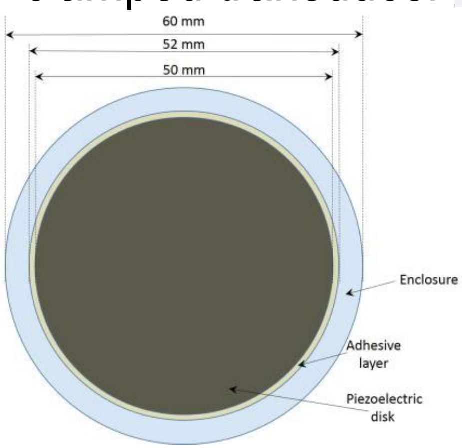
Rev. Sci. Instrum., 2020, vol. 91, 075115
2019 IEEE IUS, Glasgow, UK, 2019, pp. 1663-1665
2019 IEEE IUS, Glasgow, UK, 2019, pp. 1666-1669

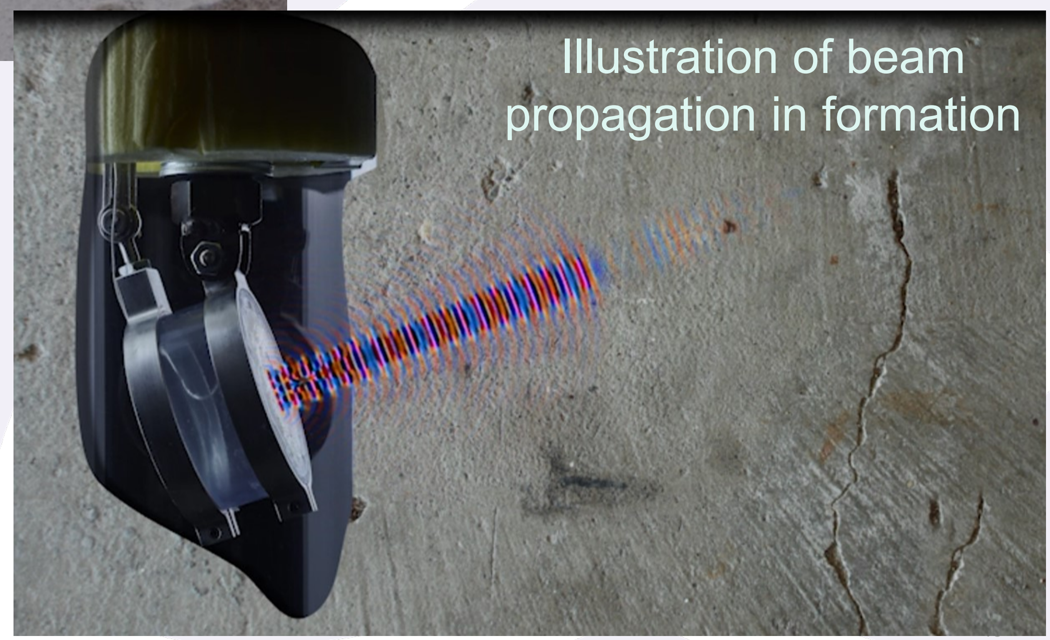
Accomplishments





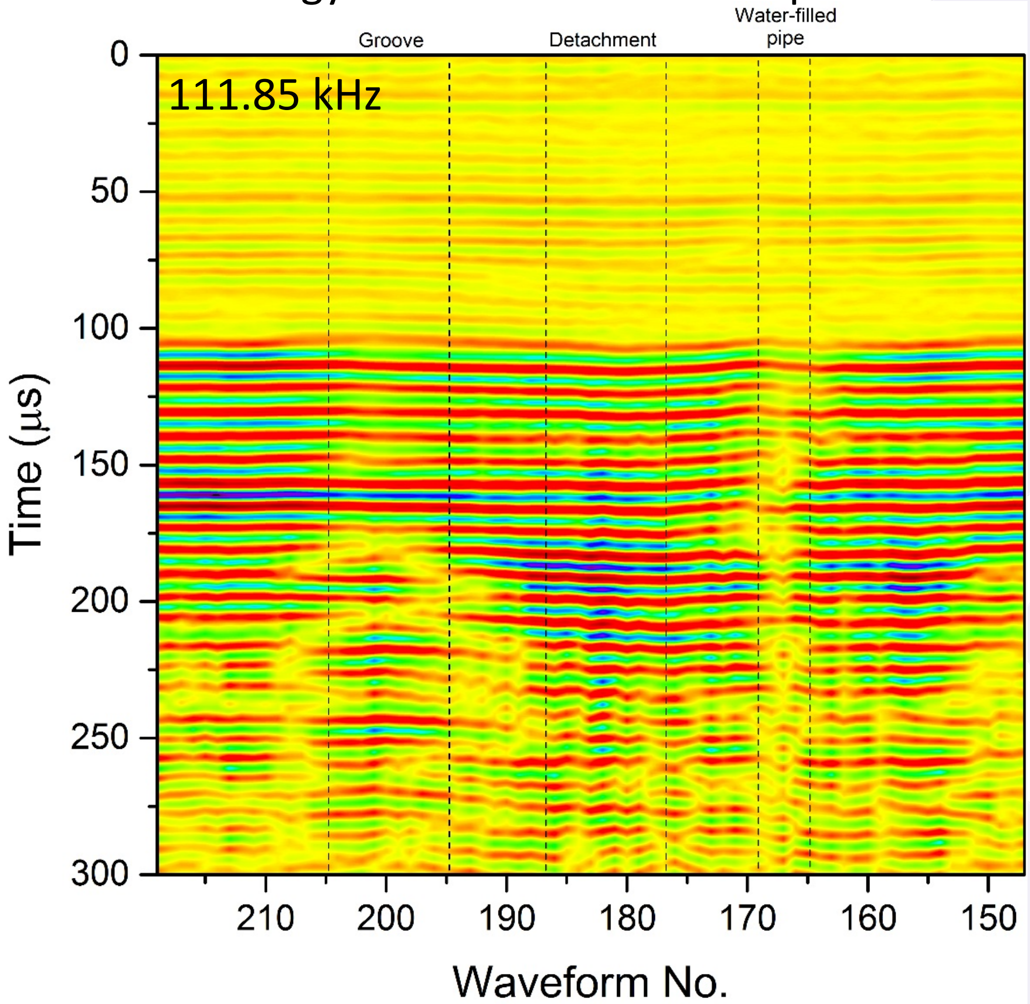
Drawing of front face of
clamped transducer

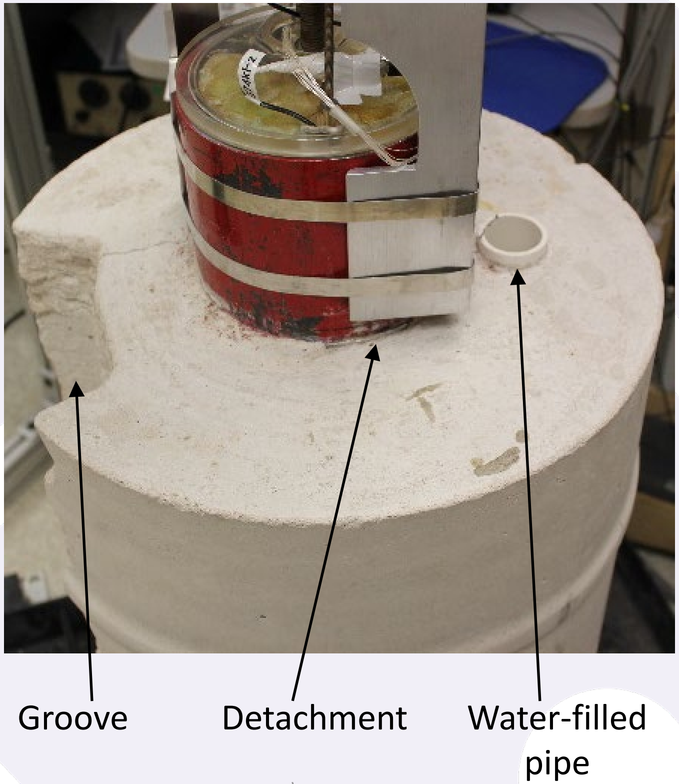


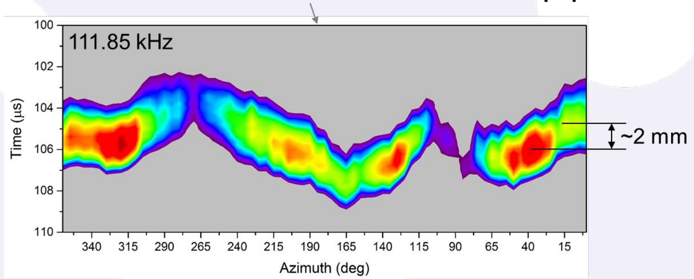


Accomplishments

Cased borehole configuration (Steel-lined cement barrel)
Reflection seismology – Common receiver representation



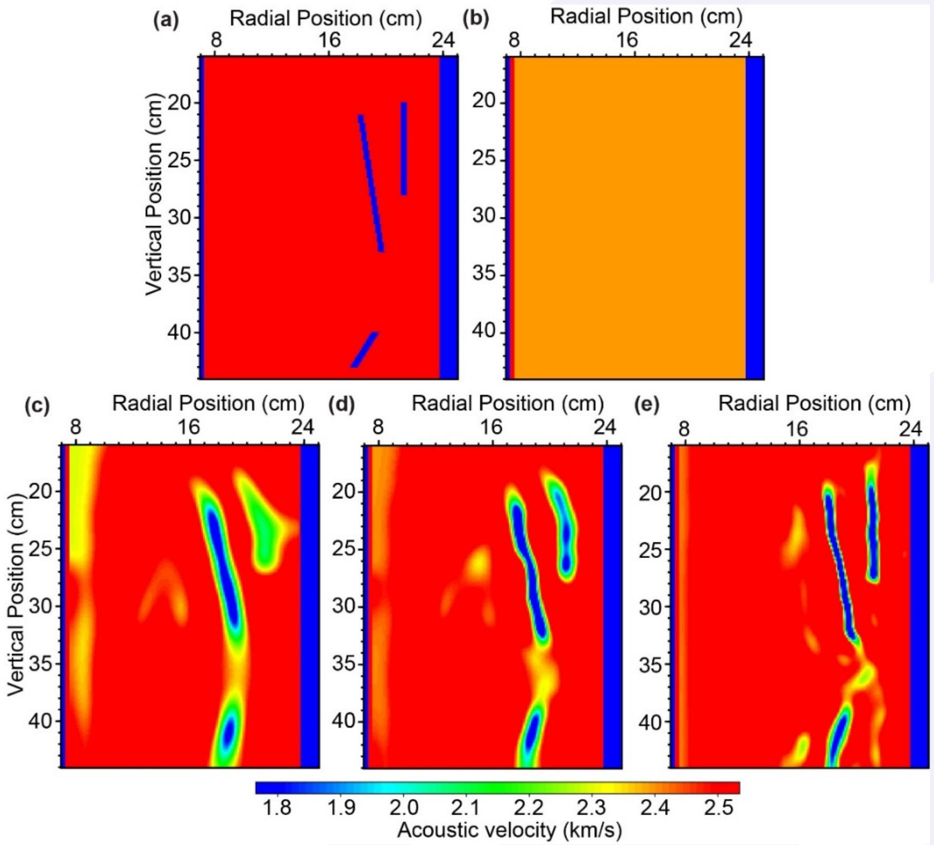




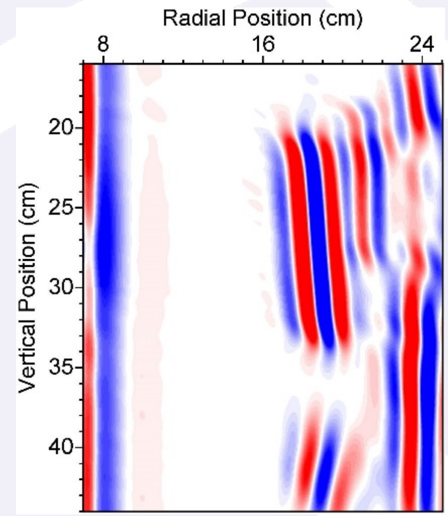
Accomplishments

LANL’s imaging approach – based on Least-square reverse-time migration

*Lianjie Huang



(a) Velocity model based on experimental data; (b) Initial velocity model used for full-waveform inversion; (c-e) Results of full-waveform inversion obtained using the center frequencies of 29 kHz (c), 42 kHz (d), and 58 kHz (e).



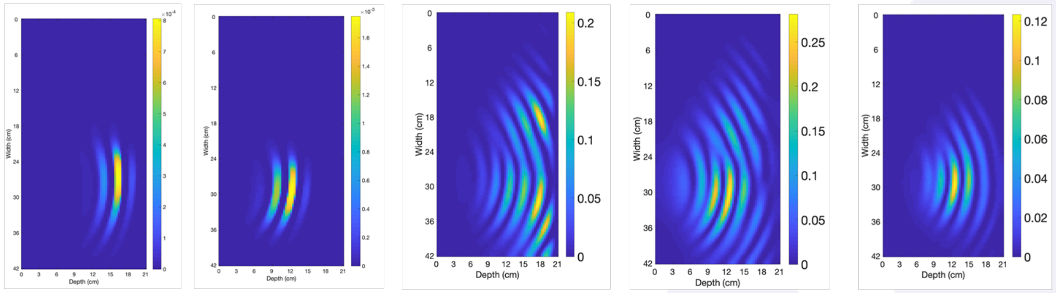
Least-squares reverse-time migration image obtained using synthetic ultrasonic data and the velocity model of full-waveform inversion

Appl. Phys. Lett., 2018, v. 113, issue 7, p. 071903

Accomplishments

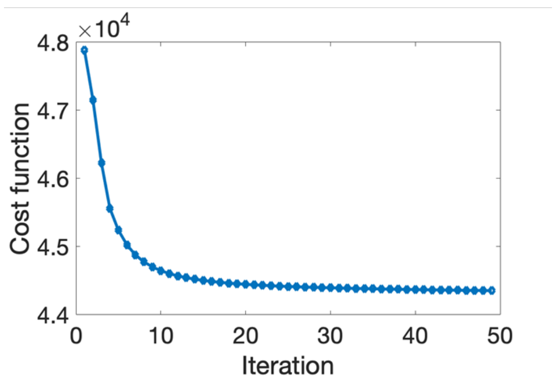
ORNL's imaging approach – based on MBIR (Model-Based Image Reconstruction)

Comparison Between Synthetic and Real Data Reconstructions



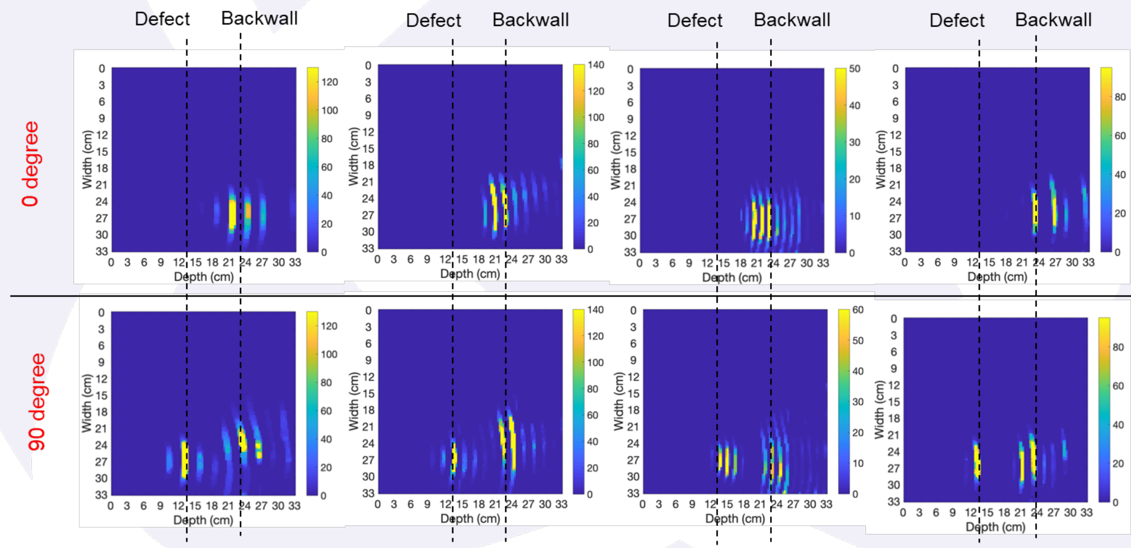
K-wave data without the notch recon | K-wave data with the notch recon | Real-data (position 37) recon, with $\phi_{s,r}^{(4)}(\nu)$ | Real-data (position 18) recon, with $\phi_{s,r}^{(4)}(\nu)$ | Real-data (position 18) recon, with $\phi_{s,r}^{(8)}(\nu)$

Cost function value vs iteration for one of the reconstructions.



Reconstruction

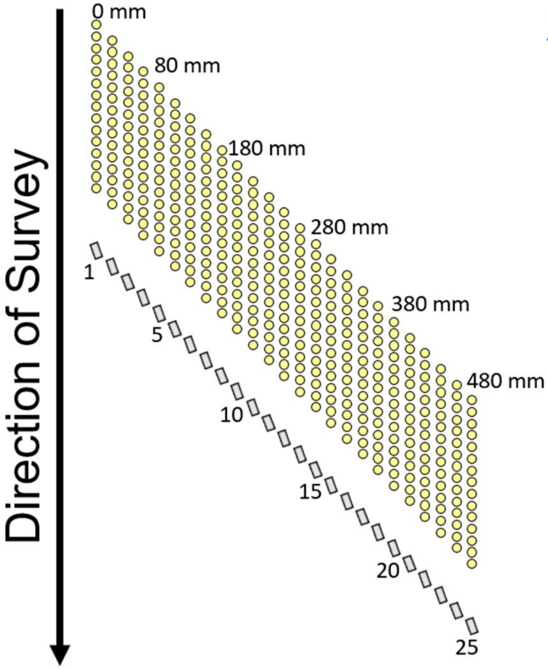
- Backwall is expected to be seen around 22~23 cm depth.
- Defect is around 12~13 cm depth.



Excitation frequency = 103.38 KHz | Excitation frequency = 162.316 KHz | Excitation frequency = 220.554 KHz | Jointly reconstructed

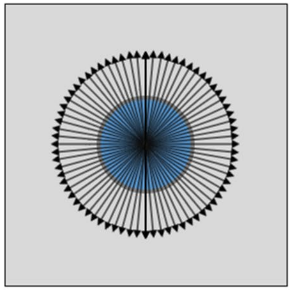
Computation time (on a personal laptop): It takes around 40 seconds to generate the system matrix and around one minute to get the reconstruction.

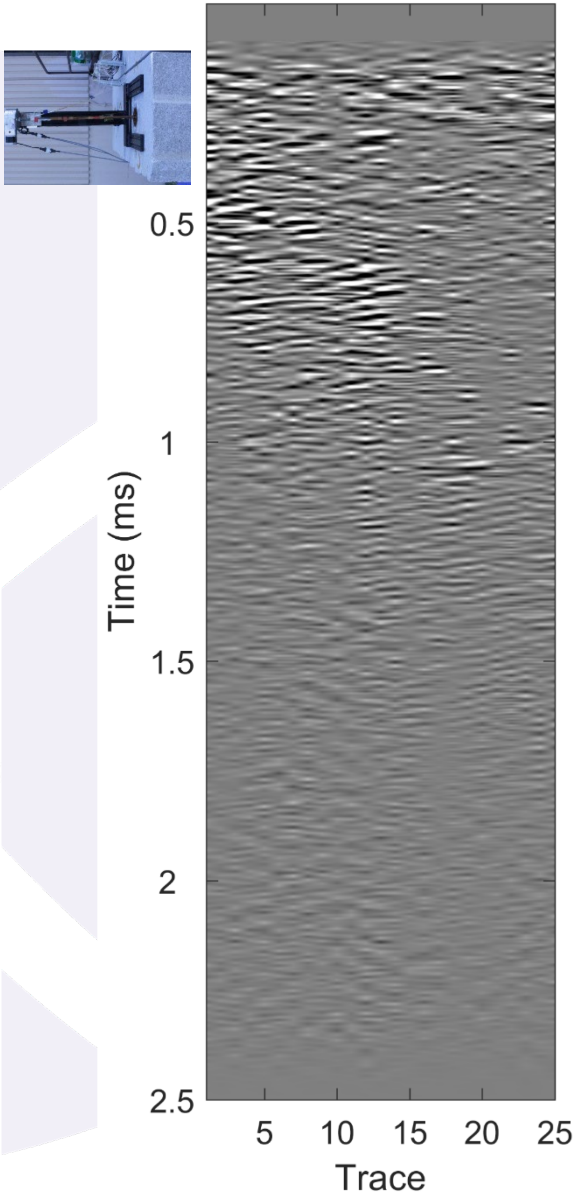
Accomplishments



Acquisition Geometry

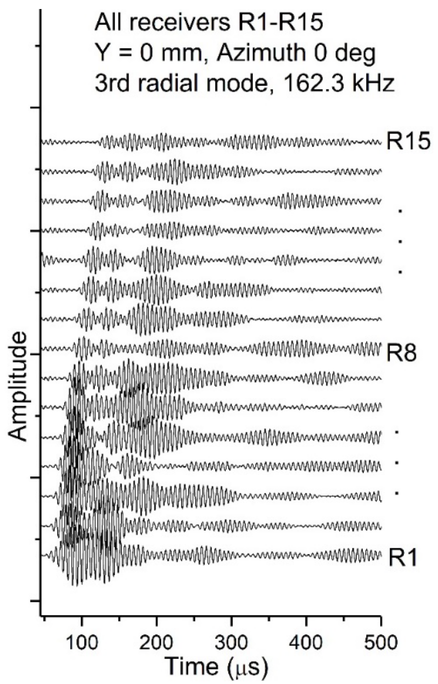
- 72 azimuths: 0° to 355°; 5° spacing
- 4 shot angle: 8°,12°,16°,20°
- 25 shot positions: 0-480 mm; 20 mm shot spacing
- 2 source frequencies: 40 kHz & 125 kHz

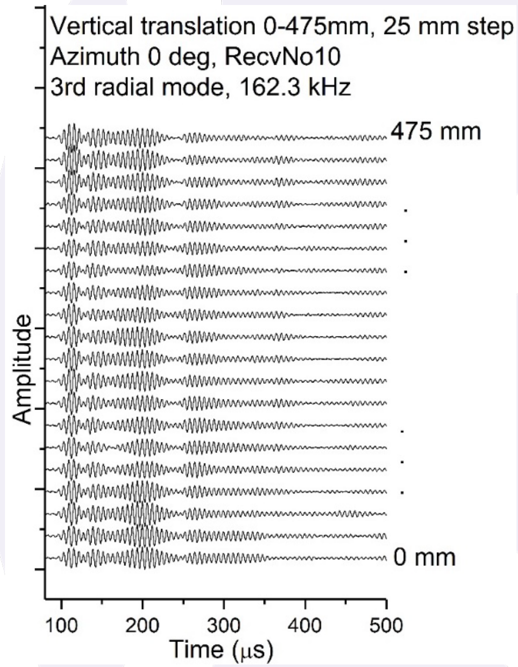


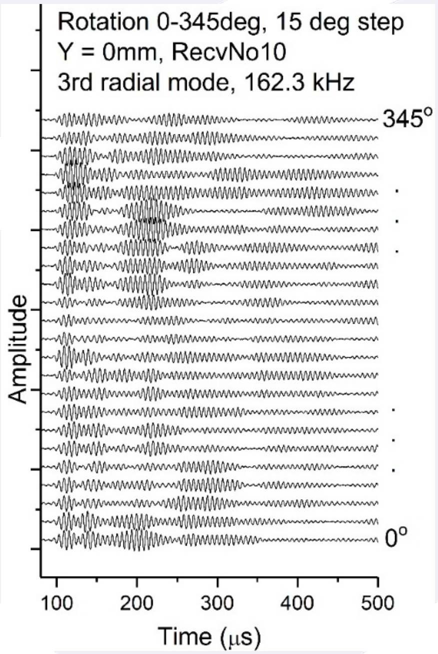


Accomplishments

Performed scans on granite blocks
360 deg rotation, and 475 mm vertical span, 5 deg and 25 mm step size

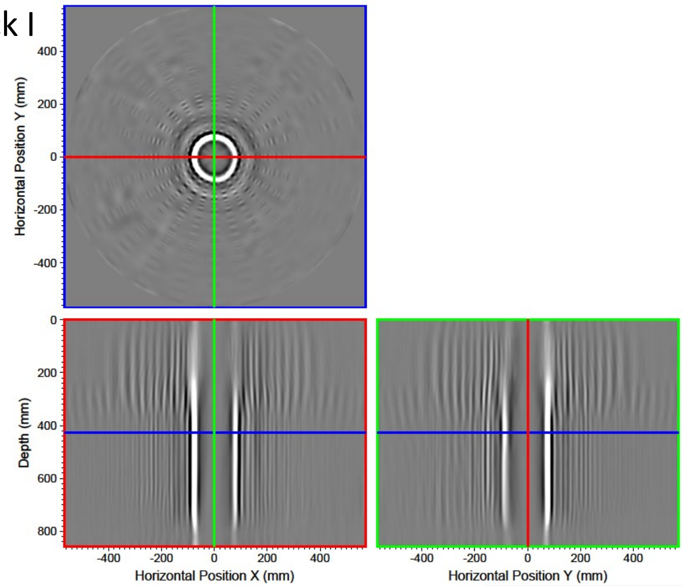




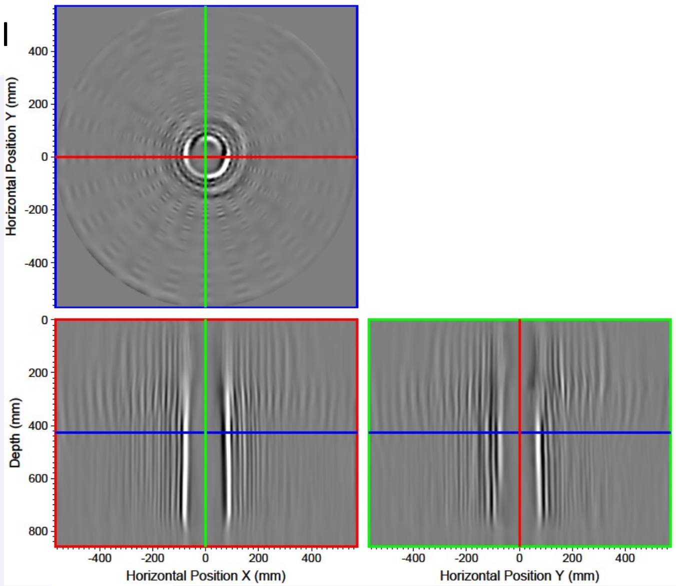


Accomplishments

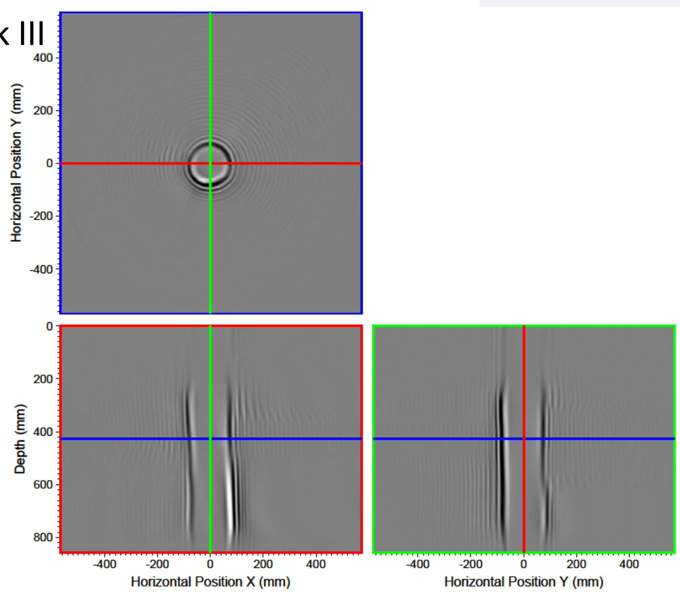
Block I



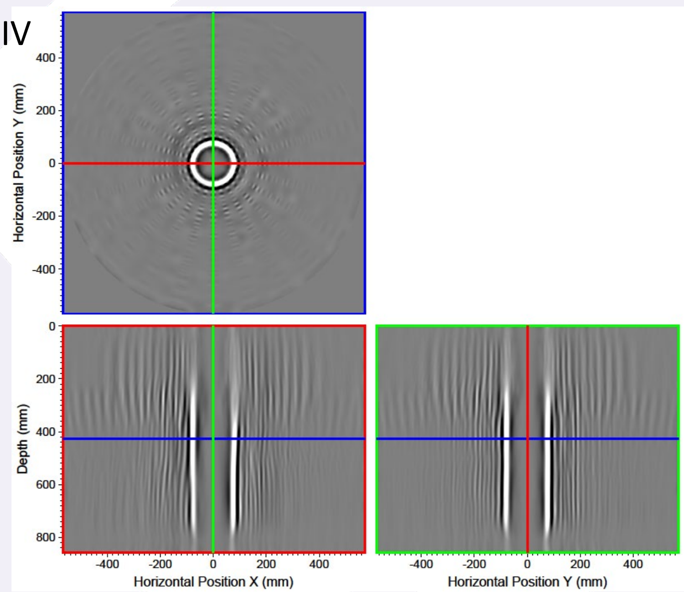
Block II



Block III



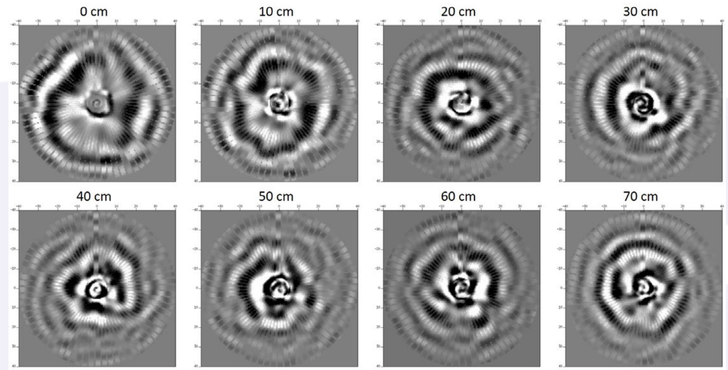
Block IV



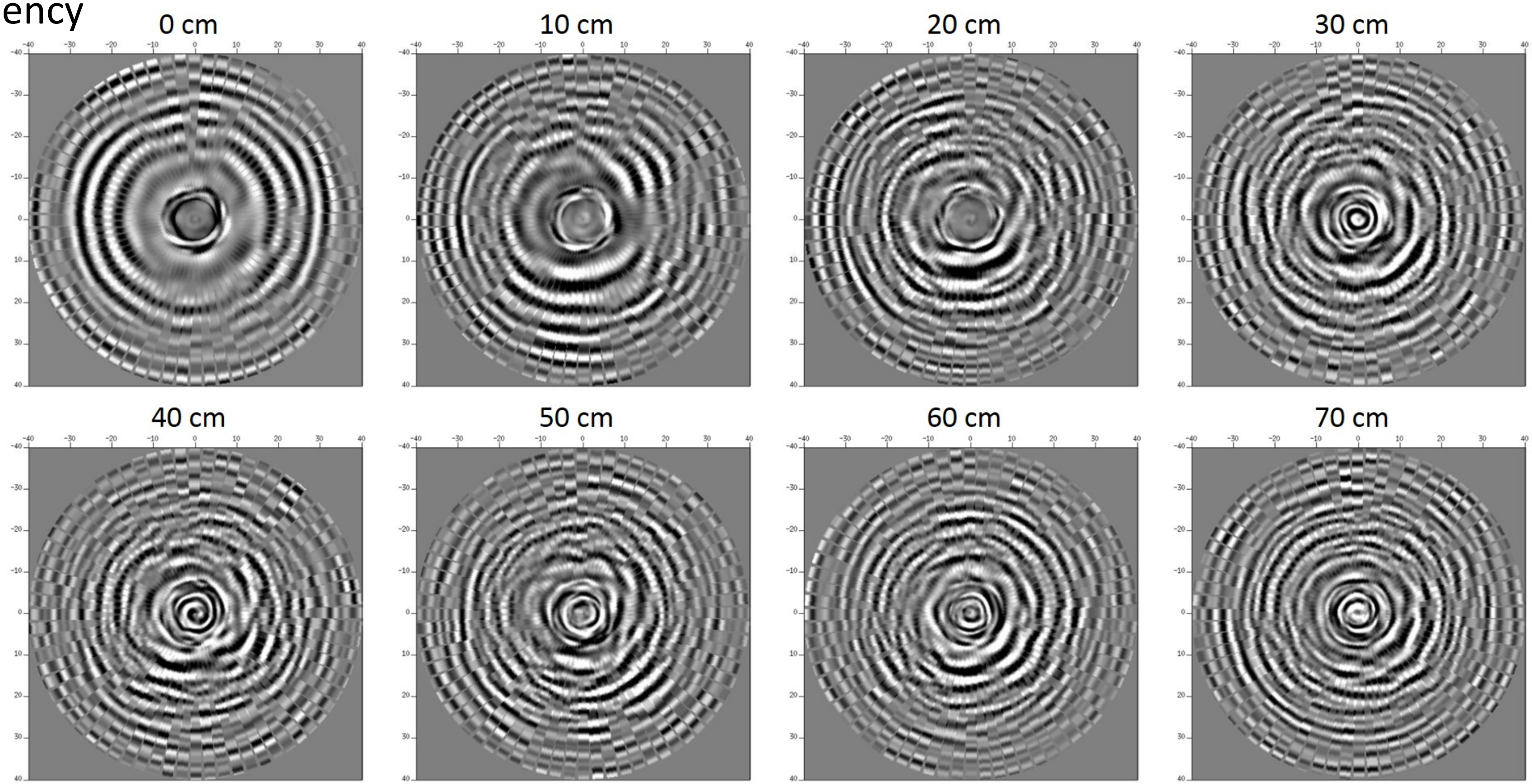
Accomplishments

Block I
½ inch nylon rope embedded

Low frequency

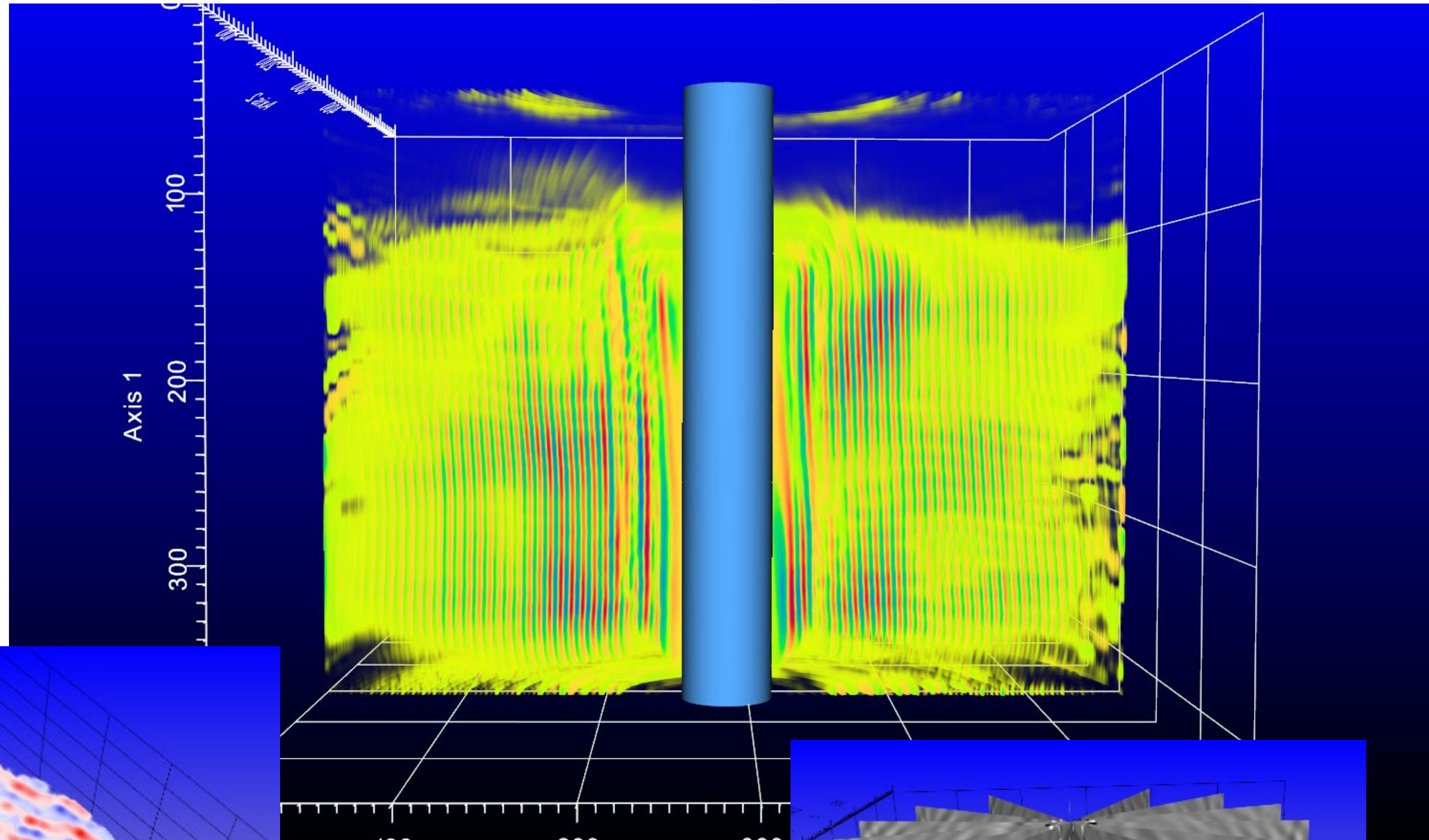


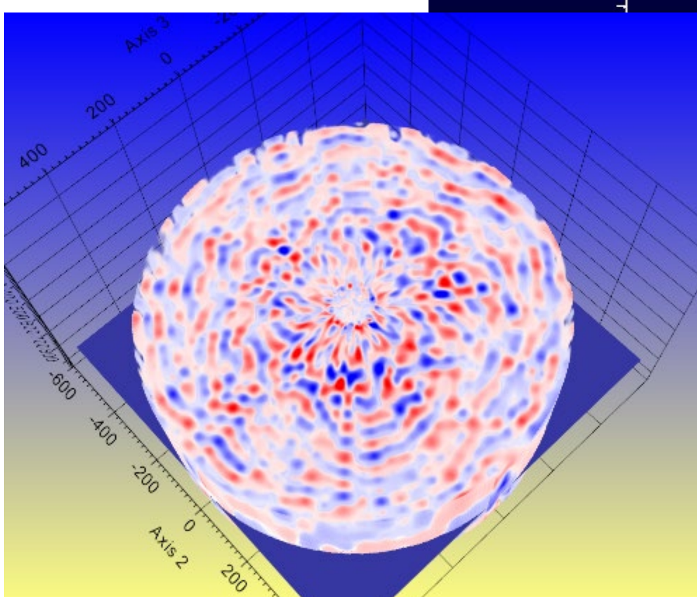
High frequency

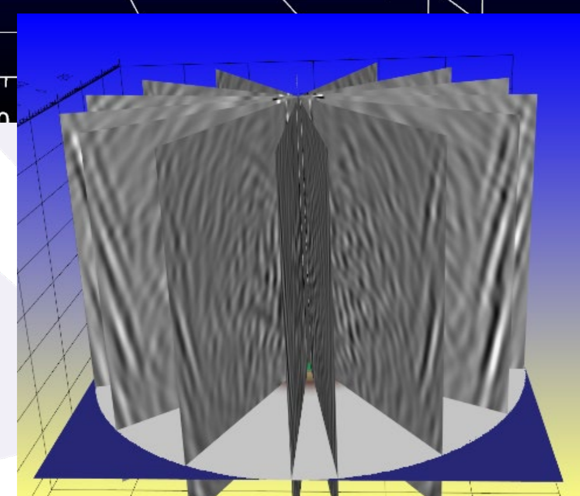


Accomplishments

Block III
Eccentricity – lean
from N to S



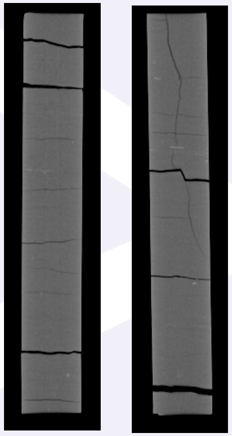




Accomplishments

- Mancos shale samples for lab-scale testing
- 18” DIA x 6” ID X 36” tall
- 4.5” OD x 4.0” ID casing
- Grouted with neat and “foam” cement

Mancos Shale cores - CT scans

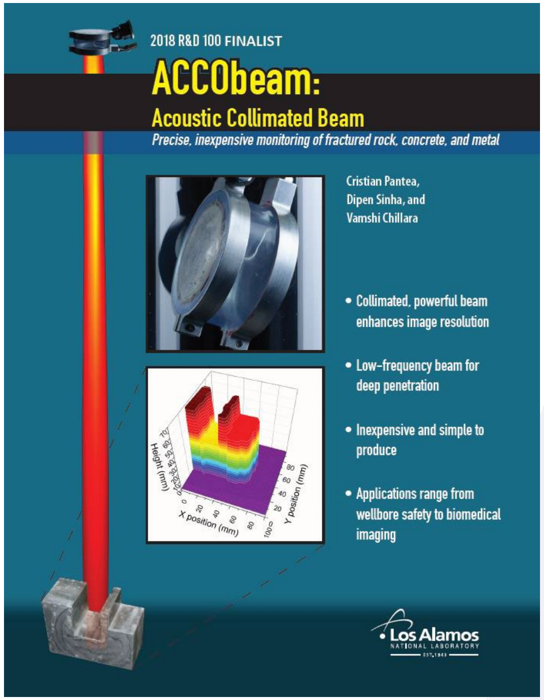


- Drilled test borehole at New Mexico Tech
  - Blue Canyon Dome in Socorro, NM
  - 2” core to 30’
  - 6.0” borehole to 30’
  - 4.5” OD X 4.0” ID casing to 30’
  - Data collection/analysis ~~pending~~

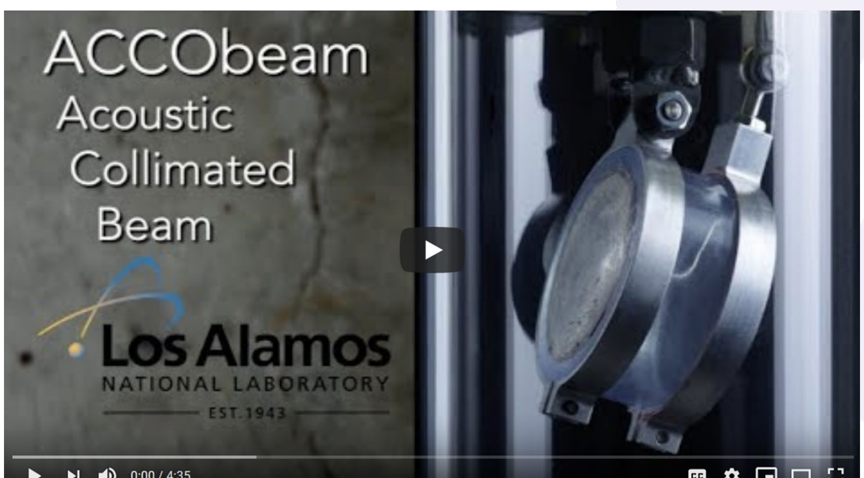
Project Summary

- There are no commercial acoustic sources that provide a collimated beam over a frequency range of 10–250 kHz in a small package that works in different media
- Developed robust operation software, speeding up data collections by about two orders of magnitude
- Developed improved acoustic source, significantly more powerful than its predecessor (~ two orders of magnitude)
- Enhanced receivers sensitivity
- Ruggedized tool for harsh conditions (high temperature, high pressure, corrosiveness, etc.)
- High azimuthal and longitudinal resolution (< 5mm)
- Extended investigation range beyond the wellbore casing

Accomplishments



www.youtube.com/watch?v=qzaPYDWXLbE



Publications

1. Rev. Sci. Instrum., 2020, vol. 91, 075115
2. Smart Mater. Struct., 2020, vol. 29, 085002
3. Ultrasonics, 2019,vol. 96, no. 7, pp. 140-148
4. 2019 IEEE IUS, Glasgow, UK, 2019, pp. 1663-1665
5. 2019 IEEE IUS, Glasgow, UK, 2019, pp. 1666-1669
6. AIP Conf. Proc., 2019, vol. 2102, pp. 040013
7. Appl. Phys. Lett., 2018, v. 113, issue 7, p. 071903
8. Wave Motion, 2018, vol. 76, p. 19-27
9. 52nd U.S. Rock Mech/Geomech Symp, 2018, ARMA
10. Appl. Phys. Lett., 2017, v. 110, issue 6, p. 064101
11. Proc of Meet on Acoustics, vol. 32(1), (2017), pp. 045013
12. Proceedings of SPIE, 2017, v. 10170, p. 101702

few more papers submitted

Conferences

- 2019 IEEE International Ultrasonics Symposium (IUS)
- 52nd U.S. Rock Mechanics/Geomechanics Symposium, 2018
- Sixth International Congress on Ultrasonics, 2017

IP

- 1 patent application (Resonance-based Nonlinear Source)
- 1 patent application (Bessel-like Acoustic Source)
- 1 provisional patent (Imaging Technique with Low-frequency Beam)